

Origin and Evolution of the Unusual Object 1996 PW

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The unusual object 1996 PW was discovered August 9, 1996 by an automated search camera operating from Mt. Haleakala Observatory in Hawaii.¹ Although asteroidal in appearance, it was soon determined that the object is in a near-parabolic orbit similar to that of a long-period comet.² Speculation has focussed on whether the object is a dormant or extinct cometary nucleus, or an asteroid, and whether it is evolving into or out of the planetary system. We examine all possible hypotheses and find that 1996 PW has most likely been a resident of the Oort cloud, probably ejected there early in the solar system's history. However we find it equally likely that 1996 PW is an extinct comet or an asteroid. We also integrate the current orbit forwards and backwards in time and show that 1996 PW is likely to be ejected from the planetary system in ~ 200 returns, with a median lifetime of 7×10^5 years.

Continued observations of 1996 PW have allowed the determination of the following orbital elements: semimajor axis = 327 AU, perihelion = 2.54 AU, inclination = 29.8° , and period $\approx 5,900$ years.³ The only objects discovered in such eccentric orbits to date are active long-period comets. However, physical observations have failed to detect any evidence for cometary activity in 1996 PW.⁴⁻⁷ The object is described as red in color, similar to S and D asteroids, and cometary nuclei. Assuming a typical cometary albedo of 0.04, 1996 PW is ~ 15 km in diameter; for a stony asteroid albedo of 0.15, its diameter is ~ 8 km.

The question thus arises, what is this unusual object and where did it come from? There are several possibilities. First, 1996 PW could be a long-period comet that has physically evolved to a dormant or extinct state, with its icy surface covered by a lag deposit of non-volatile dust grains and organics, and/or radiation processed so as to sputter away all volatiles. Second, the object could be

an ecliptic comet (i.e., a comet originally from the Kuiper belt beyond Neptune) that has evolved to a similarly dormant or extinct state, and is now evolving outward due to planetary perturbations. Third, 1996 PW could be an asteroid that was ejected to the Oort cloud (i.e., the cloud of comets surrounding the planetary system at near-interstellar distances; the Oort cloud is the source of the long-period comets). As such, it most likely experienced the same dynamical evolution as the long-period comets, probably ejected early in the solar system's history, and recently thrown back into the planetary system by stellar and galactic perturbations. Lastly, 1996 PW could be an asteroid that has recently been perturbed out of a stable orbit by the planets, and is evolving outward.

We performed a series of dynamical simulations and calculations to test each of these hypotheses. First, we assumed that 1996 PW had come from the Oort cloud and followed its evolution inward using a Monte Carlo simulation.⁸ The dynamical simulation assumed that comets random walk in orbital energy, $1/a$ (the inverse of the semimajor axis), due to planetary perturbations, with the r.m.s. magnitude of the perturbation determined by the object's perihelion distance and inclination. The simulation assumed that objects are lost by ejection to interstellar space or by being returned to the Oort cloud ($a > 10^4$ AU), where galactic and stellar perturbations will likely raise the perihelion distance out of the planetary region. No physical loss mechanisms were included.

Results for 10^7 hypothetical objects with origin in the Oort cloud and the perihelion distance and inclination of 1996 PW are shown in Figure 1, which gives the probable age of 1996 PW versus the number of perihelion passages. The distribution is sharply peaked with a maximum value at only 6 returns, and a long tail. The median number of returns is 28, and 95% of the comets with semimajor axes similar to 1996 PW have ages of 391 returns or less; 99% have made less than 774 returns.

How long then does it take a comet to evolve to a dormant or extinct state? Since cometary volatiles only sublime when the nuclei are close to the Sun, the age of comets is best measured in terms of the number of perihelion passages or returns. Estimates of the physical lifetimes of comets as active bodies vary considerably. As a minimum, one can consider periodic comets Encke and Halley, which both have much smaller perihelion distances than 1996 PW, and which have been observed on 56 and 30 returns, respectively.⁹ Estimates of the age of comet Halley based on studies of the associated meteoroid streams range from 2.3×10^4 to over 2×10^5 years, which translates into 300–2,600 returns at its current orbital period.^{10,11} The sublimation lifetime for a 1 km radius, low-albedo water ice sphere with a perihelion distance similar to that of 1996 PW is $>5,000$ returns.¹² Dynamical studies of the evolution of Jupiter-family comets from the Kuiper belt suggest a median physical age of 12,000 years as active comets, or typically about $\sim 1,600$ returns.¹³ Based on these estimates, we assume a conservative physical lifetime for comets of half this latter value, or 800 returns.

It thus appears extremely unlikely that 1996 PW could have evolved to a dormant or extinct state in the median dynamical age of only 28 returns, and unlikely at the 99% level that it could have done so in a physical lifetime of < 800 returns. The estimated flux of long-period comets at the Earth's orbit is $\sim 10 \text{ yr}^{-1}$ (ref. 14), suggesting $\sim 25 \text{ yr}^{-1}$ at 2.5 AU, the perihelion distance of 1996 PW (this is a conservative estimate since the cometary perihelion distribution increases with heliocentric distance¹⁴). Combined with the physical lifetime estimate above, this predicts a flux of ~ 0.25 extinct long-period comets yr^{-1} at $q \leq 2.5 \text{ AU}$. From our Monte Carlo simulation described above, we expect that 12% of the comets will be in orbits similar to that of 1996 PW ($a = 200\text{--}500 \text{ AU}$). Thus, we find that the expected flux of extinct long-period comets is $\sim 0.03 \text{ yr}^{-1}$.

Could 1996 PW be an asteroid which was ejected to the Oort cloud and which has now been

thrown back into a planet-crossing orbit? Although there has been some speculation on asteroids being placed in the Oort cloud,¹⁵ the problem has never been pursued in detail. However, new dynamical simulations by Levison and Duncan (work in progress) find that 8% of the material initially in orbits between Jupiter's orbit and the 2:1 dynamical resonance at 3.28 AU (roughly the outer edge of the main asteroid belt) is ejected to bound orbits with $a > 10^4$ AU, i.e., in the Oort cloud. Given an initial surface density of condensed solids, i.e, rocky/carbonaceous bodies, in the solar nebula of 30 g cm^{-2} at the Earth's orbit, and assuming the surface density varied as $\bar{r}^{-3/2}$ through this region,¹⁶ there would have been 1.6 Earth masses (M_{\oplus}) of rocky/carbonaceous bodies between 3.28 and 5.2 AU. If 8% went into the Oort cloud, then one would expect $0.13 M_{\oplus}$ of asteroids in the Oort cloud. This compares with a total cometary mass of $\sim 16 M_{\oplus}$ originally in the outer, dynamically active Oort cloud, assuming a current population of 10^{12} comets, a mean nucleus mass of $3.8 \times 10^{16} \text{ g}$, and 40% of the original Oort cloud population surviving.^{14,17} Thus, 0.8% of the objects perturbed back into the planetary system from the Oort cloud may be asteroids rather than comets, assuming that the size distributions are similar. We suggest that this is a conservative number since considerably more rocky objects must have been ejected from orbits interior to 3.28 AU during the dynamical clearing of the planetary zones.

Given the ratio found above and assuming a population of 10^{12} comets in the outer Oort cloud, then there are currently $\sim 8 \times 10^9$ asteroids in the outer cloud. Again, taking an estimated flux of ~ 25 long-period comets yr^{-1} at the perihelion distance of 1996 PW, and 12% of the objects in orbits similar to 1996 PW, predicts a flux of ~ 0.024 asteroids yr^{-1} , close to the flux of extinct long-period comets.

A third explanation for the origin of 1996 PW is that it is an extinct ecliptic comet currently evolving out of the planetary system. Analysis of previous dynamical simulations of the evolution

of ecliptic comets from the Kuiper belt,¹³ find that only 3×10^{-8} of the population will be found at any time in orbits with $a = 200\text{--}500$ AU and $q < 3$ AU, similar to that of 1996 PW. The total steady-state population of ecliptic comets, given the observed population of active Jupiter-family comets, is estimated to be $\sim 10^7$ objects.¹³ Thus, one would predict ~ 0.3 ecliptic comets currently in an orbit similar to that of 1996 PW. Assuming a 5,900 year orbital period, the flux of such objects is $\sim 5 \times 10^{-5} \text{ yr}^{-1}$.

Next, we consider if 1996 PW could be an asteroid recently ejected from the planetary system by the Jovian planets. Approximately 2,500 asteroids > 1 km diameter are currently evolving out of the main asteroid belt.¹⁸ Based on dynamical simulations by Levison and Duncan (in progress), we estimate that $< 6 \times 10^{-5}$ of these asteroids are expected to be in orbits similar to that of 1996 PW, or < 0.2 objects. Assuming a 5,900 year period, the expected flux is $< 4 \times 10^{-5} \text{ yr}^{-1}$.

Finally, ~ 1200 objects from the Jupiter Trojan asteroid clouds are estimated to be currently evolving out of the planetary system.¹⁹ Approximately 2×10^{-4} of these objects are expected to be in orbits similar to that of 1996 PW, or only ~ 0.2 objects. Assuming the orbital period of 1996 PW, the flux is $\sim 3 \times 10^{-5} \text{ yr}^{-1}$.

Our results are summarized in Table 1. We conclude that the most likely scenario for the origin of 1996 PW is that it is from the Oort cloud. However we find that it is equally likely that 1996 PW is an extinct long-period comet or an asteroid. We favor the latter interpretation because of the conservative approach we have taken in estimating the number of asteroids in the Oort cloud, and the likelihood that physical lifetimes for comets are greater than 800 returns. The asteroids were likely ejected to the Oort cloud early in the solar system's history during the clearing of the interplanetary zones. This asteroid has now been returned to the planetary region by the same combination of stellar and galactic perturbations that feed long-period comets in towards the Sun.

What is the future for 1996 PW? We integrated 24 test particles with initial orbits similar to 1996 PW, both forward and backward in time, until the objects were either ejected from the planetary system or perturbed to semimajor axes $> 10^4$ AU, allowing them to be recaptured to the Oort cloud. The fraction of survivors versus age is shown in Figure 2. The median age is 200 returns with a typical lifetime of 7×10^5 years.

Given the results above, we suggest that 1996 PW may be only the first detected member of a likely population of asteroids which are resident in the Oort cloud, some of which may now be passing through the planetary region on highly eccentric orbits. We hope that the discovery of this new class of objects will increase as additional automated search programs such as the one on Mt. Haleakala come on line.

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Table 1. Probable annual flux of objects in orbits similar to that of 1996 PW, assuming different origin scenarios, and normalized to a semimajor axis range of 200–500 AU and a perihelion distance less than 3 AU.

Extinct long-period comet	$> 3.6 \times 10^{-2}$
Oort cloud asteroid	$> 2.9 \times 10^{-2}$
Extinct ecliptic comet	5×10^{-5}
Main belt asteroid	$< 4 \times 10^{-5}$
Trojan asteroid	3×10^{-5}

Figure captions:

Figure 1. Probable dynamical age of an object evolving inward from the Oort cloud to the current orbit of 1996 PW, measured in the number of perihelion returns by the object. An initial semimajor axis of 25,000 AU was assumed. Because 1996 PW is in a relatively low inclination, large perihelion orbit, perturbations by Jupiter are relatively large and the orbital evolution can be very rapid.

Figure 2. Dynamical lifetimes for 24 test particles in orbits similar to the current orbit of 1996 PW, integrated forward and backward in time. The median dynamical age is 7×10^5 years, or about 200 returns. This is somewhat longer than the expected dynamical lifetime for Jupiter-family comets evolving out of the planetary system.¹³ Roughly half the objects are ejected to interstellar space, while the other half are returned to orbits in the Oort cloud.

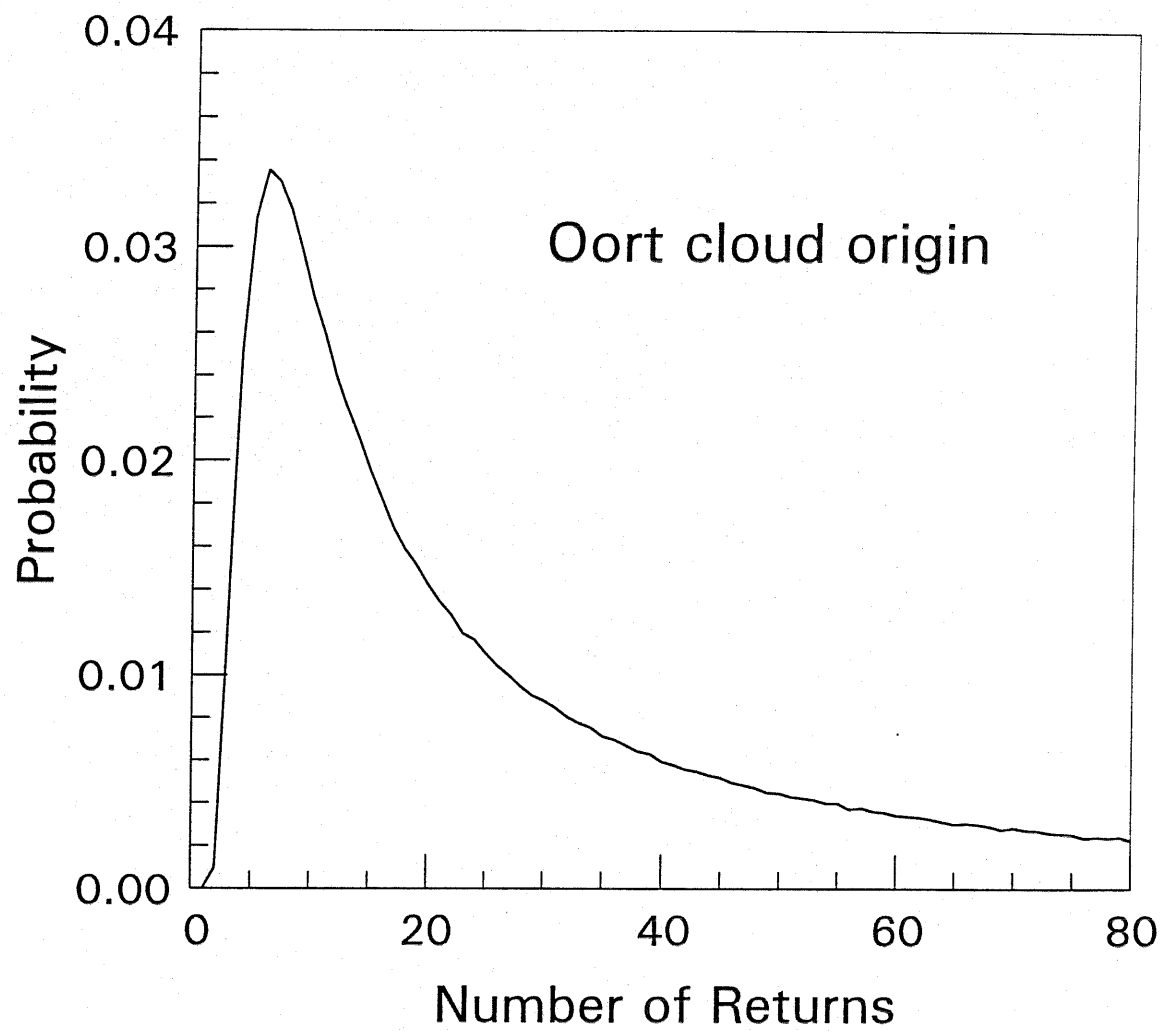


Figure 1

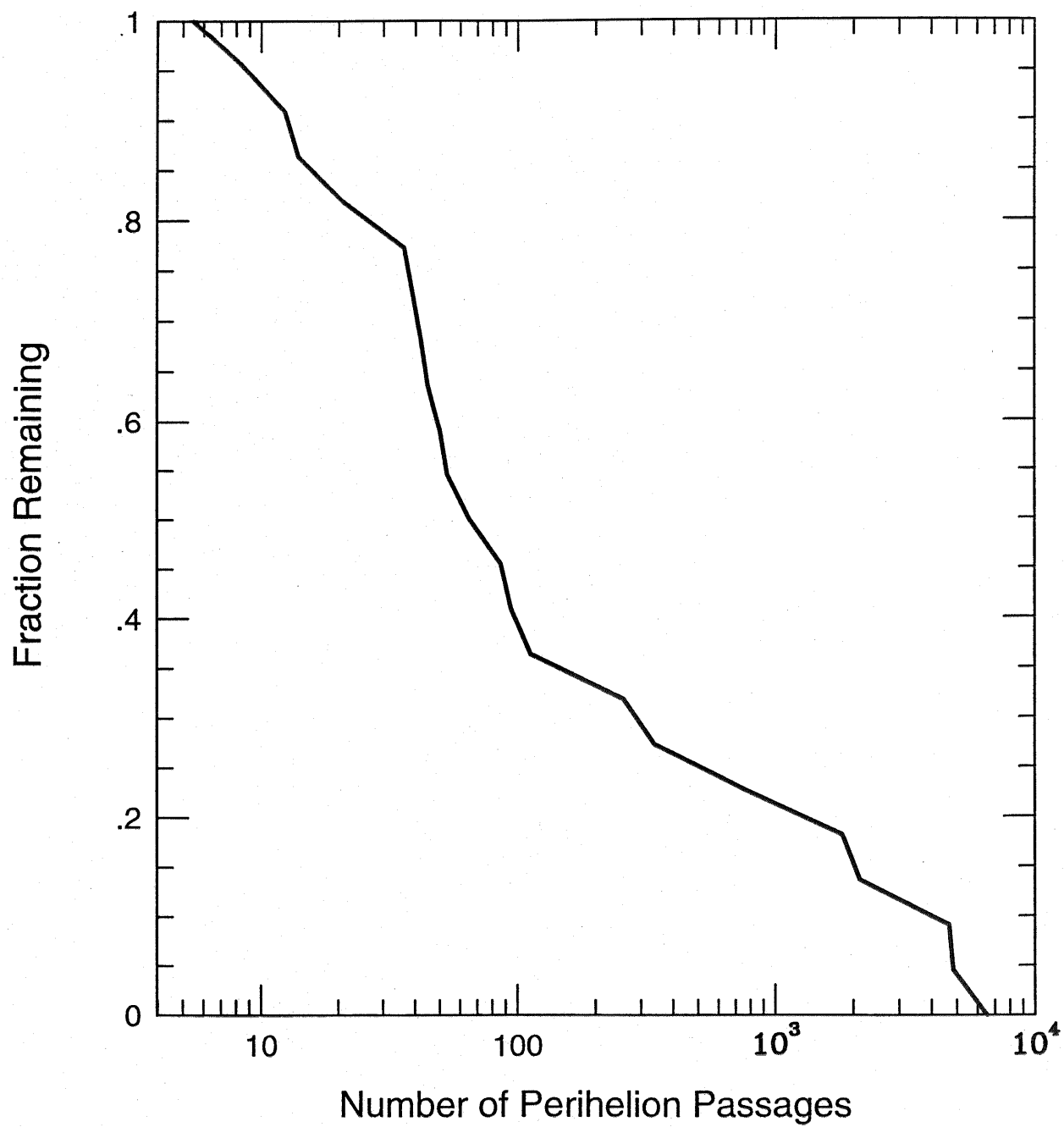


Figure 2